COMPARATIVE ANALYSIS OF BIOMASS THERMAL GENERATORS / *ANALIZA COMPARATIVA PRIVIND GENERATOARELE TERMICE PE BIOMASA*

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ABSTRACT

The thermal generator made within the project PN-III-P2-2.1-PTE-2021-0306, 87PTE with the title "Technologies and innovative drying equipment with energy independence, for mountainous and isolated areas" is intended to equip the small capacity convective dryer (drying surface of 4 m^2 and loading 20-100 kg), with total energy independence with respect to the electricity network, with the help of which to implement and validate the technologies for dehydrating berries, mushrooms, medicinal and aromatic plants from spontaneous flora, respectively fruits from the orchards of small agricultural producers in isolated hill and mountain areas. The thermal energy required for the dehydration process will be produced with the help of a thermal generator operating on the TLUD principle, from biomass existing locally. The air-to-air heat exchanger will provide a clean drying agent (hot air), with major effects on the food safety of consumers.

REZUMAT

Generatorul termic realizat in cadrul proiectului PN-III-P2-2.1-PTE-2021-0306, 87PTE cu titlul "Tehnologii si echipament de uscare inovativ cu independenta energetica, pentru zone montane si izolate" este destinat echiparii uscatorului convectiv de capacitate mica (suprafata de uscare 4 m^2 si incarcarea 20-100 kg), cu independenta energetica totala fata de reteaua de energie electrica, cu ajutorul caruia sa fie implementate si validate tehnologiile de deshidratare a fructelor de padure, ciupercilor, plantelor medicinale si aromatice din flora spontana, respectiv a fructelor provenite din livezile micilor producatori agricoli din zonele izolate de deal si de munte. Energia termica necesara procesului de deshidratare va fi produsa cu ajutorul unui generator termic cu functionare pe principiul TLUD, din biomasa existenta la nivel local. Schimbatorul de caldura, de tip aer-aer, va furniza un agent de uscare curat (aer cald), cu efecte majore privind siguranta alimentara a consumatorilor.

INTRODUCTION

Through the elaboration of the Technical and comparative study on the technical solutions of convective dryers, it was concluded that the application of the synergistic CHAB concept for obtaining thermal energy necessary in the process of dehydration of vegetable products, leads to a superior utilization of biomass, producing thermal energy and biochar. Considering that the minimum efficiency of the heat exchangers is 0.85, it follows that a maximum of 1.5 MJ/kg bm is returned to the atmosphere.

Installations destinated for production of biochar (that do not apply the CHAB concept), partially use the thermal energy of the gases resulting from pyrolysis to maintain the pyrolysis process (endothermic) and/or to pre-dry the treated biomass. From a kg of biomass with an average humidity of 15%, which has a lower calorific value of 16 MJ/kg bm, about 20% biochar results and the difference of 80% of the biomass is completely gasified. The calorific value of gasified biomass is 14 MJ/kg bmg. For the pyrolysis of one kg of biomass, an average energy of 2 MJ is required. Considering that the conversion efficiency is 0.9 and the combustion efficiency is 0.95, it results in an available thermal energy of 9.6 MJ/kg bm. Decreasing the energy consumption for pyrolysis maintenance results in an energy of 7.6 MJ/kg bm, which is discharged into the atmosphere. This value represents almost 50% of the thermal energy that could be obtained from the direct combustion of biomass. It turns out that this method of biomass recovery represents a great waste of energy potential, just to obtain biochar with a high value on the market *(Edmond MAICAN, 2015)*.

MATERIALS AND METHODS

The chemical processes produced and the arrangement of the biomass layers in which they occur in an "updraft" type gasifier are shown in fig. 1.

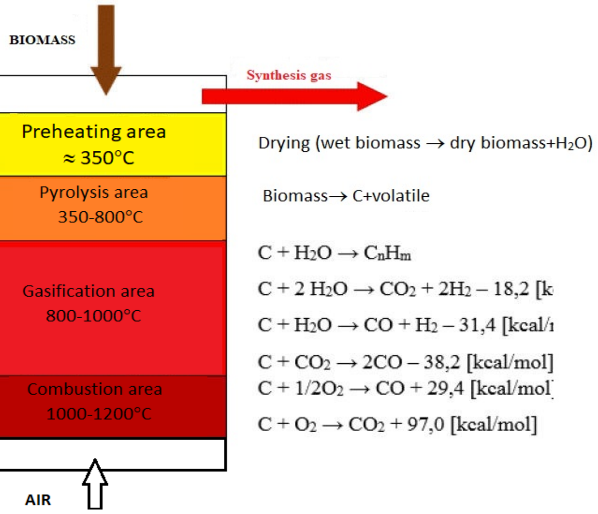


Fig. 1 - Chemical processes produced in an updraft gasifier

Pyrolysis consists in the thermochemical decomposition of solid biomass, a process that takes place at temperatures of 300-800°C, in the absence of oxygen. This process results in heat, various gases (hydrogen, methane, carbon monoxide, etc.), bio-oil and coal. Combustible gases can be separated and captured, and the resulting coal, also called biochar, can be used as a fertilizer and agricultural amendment, a use that also represents an efficient and economical way of carbon sequestration.

For each type of biomass and a given pressure, there are two parameters that influence the products resulting from pyrolysis, namely the reactor temperature and the time, fig. 2. *(Andresen, J., Lim, X. 2011)*

High temperatures and a short period exposure of biomass favor gasification reactions, while lower temperatures favor the formation of coal (biochar).

When the main goal is to obtain bio-oil, maximizing the quantity can be done by adjusting the two parameters. If the aim is to obtain the largest possible quantities of biochar, the temperatures will have to be kept below the value of 300 °C.

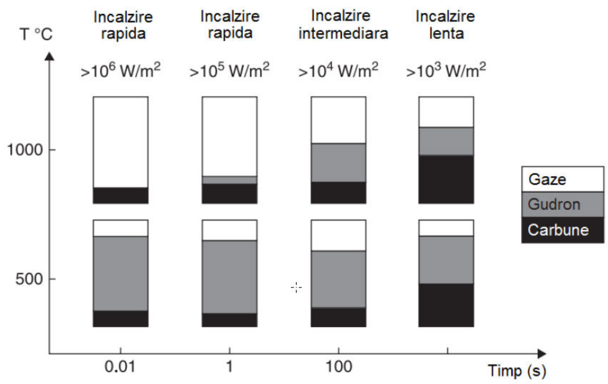


Fig. 2 - Variation of pyrolysis products with temperature and exposure time

Gasification is the thermochemical process through which solid biomass turns into gas at temperatures of 800-1300 °C. The obtained gas is called synthesis gas/syngas or producer gas /gas generator and is a combustible mixture of hydrogen, carbon monoxide, methane, nitrogen, carbon dioxide, sulfur, alkaline compounds and tars, tab.1 *(Panwar, N., Kothari, R. and Tyagi, V., 2012)*.

Table1

Constituents of synthesis gas

Name compound	**Chemical formula**	**Wet gas, [vol.%]**	**Dry gas, [vol.%]**
Carbon monoxide	CO	21,0	22,1
Carbon dioxide	CO_2	9,7	10,2
Hydrogen	H_2	14,5	15,2
Water vapours	H_2O	4,8	-
Methane	CH_4	1,6	1,7
Nitrogen	N_2	48,4	50,8
Other informations			
Superior calorific power (relative to the wet mass)			5506 kJ/Nm^3
Superior calorific power (relative to the dry mass)			5800 kJ/Nm^3
Air required for gasification			1 kg air/ 2,38 kg wood
Air required for combustion			1 kg air/1,15 kg wood

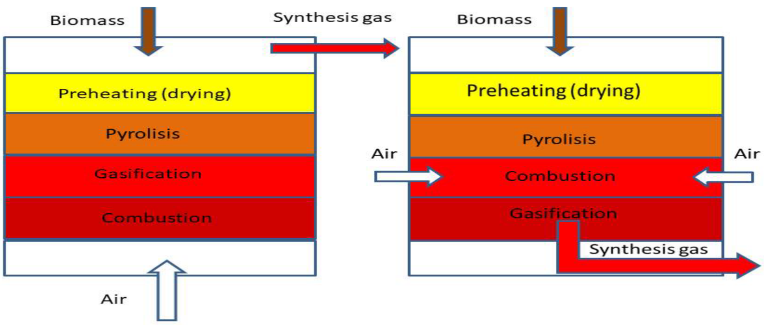
In principle, a limited amount of oxygen or air is introduced into the reactor so that, through the combustion of a fraction of the biomass, carbon dioxide and energy are generated. The released energy initiates a second reaction that converts the biomass into hydrogen and carbon monoxide. The latter reacts with the water molecules from the initial drying of the biomass, resulting in methane and again carbon dioxide.

Gasifiers are classified according to the type of fuel used, the way air is introduced into the fuel mass and the type of combustion bed.

Fixed-bed gasifiers are simple constructions, consisting of a cylindrical reactor in which the biomass is located, with feeding on the upper part, in which the generated gas moves vertically (up or down). They are characterized by low ash content and low gas velocity.

Air can enter:

- at the lower part of the reactor, circulating through the biomass layer towards the upper part (updraft or countercurrent gasifiers - fig. 3 a);
- on the upper part, circulating from top to bottom (downdraft or equicurrent gasifiers, fig. 3 b);
- crossection to the mass of material (crossdraft or crossection gasifiers).



a) b)

Fig. 3 - Types of fixed bed gasifiers: (a) updraft; (b) downdraft

The first type of thermal module in the CHAB concept with which biochar was produced was the one with the TLUD type micro-gasification process.

In principle, the up-draft gasification process is not a biochar producer and as a result most current installations use variants of the down-draft process.

Installations that produce both heat and biochar are divided into two categories:

- with two processes in parallel: TLUD type gasification that produces thermal energy and biochar and a second subsystem, put in series, in which the thermal energy produced before is used for the pyrolysis of another amount of biomass, which produces combustible gases burned in the continuation of those from gasification, thermal energy that can be used in thermal applications;

- with a controlled gasification process from which biochar can also be obtained.

An example of an installation with a controlled gasification process from which biochar can also be obtained is the DRAGON type installation, produced by CHIP ENERGY (USA), which can gasify a wide variety of biomass, produces hot water or hot air and biochar in proportion of 15-20%. Figure 4 shows the functional diagram, and Figure 5 shows the system mounted in a transportable container *(First energy, 2014)*.

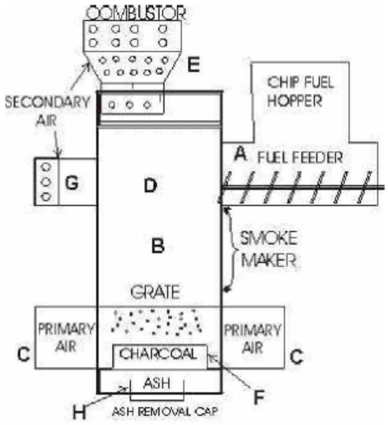


Fig. 4 - Functional diagram of AVUD type installation from CIP ENERGY

A. Conveyor feed hopper B. Biomass layer C. Gasification air inlet D. Gas producer collection area E. Combustion air inlet F. Biochar area G. Combustion regulation air inlet H. Ash tray

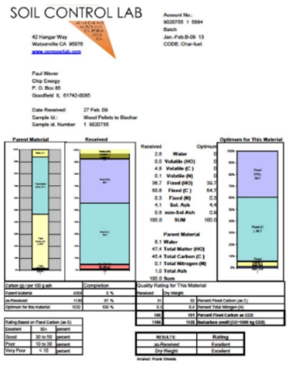
Fig. 5 - DRAGON type installation from CIP ENERGY

A. Gaz producer of 60kWt ; B. Feed hopper with biomass ; C. Primary air fan; D. Secondary air fan; *E. Draft* fan *;F. Automatic driving system ; G. Monitoring operator J. Biochar conveyor K. Recipient ; L. Biomass exterior hopper; M. Steam boiler type flach N. Pumps and pipes of hot water*

The burner for the production of hot air is mounted at the exit of the gas stove.

Fig. 6 - The burner for hot air production of DRAGON type instalallation

The results regarding produced biochar composition by the DRAGON system from CHIP ENERGY are presented in analysis reports from fig.7.



Chip Energy Biochar Material		
Received		Optimum
2.6	Water	0
0.0	Volatile (HO)	0
4.8	Volatile (C)	0
0.1	Volatile (N)	0
36.7	Fixed (HO)	39.7
50.6	Fixed (C)	54.7
0.3	Fixed (N)	0.3
4.1	Sol. Ash	4.4
0.8	non-Sol Ash	0.9
100.0	SUM	100.0

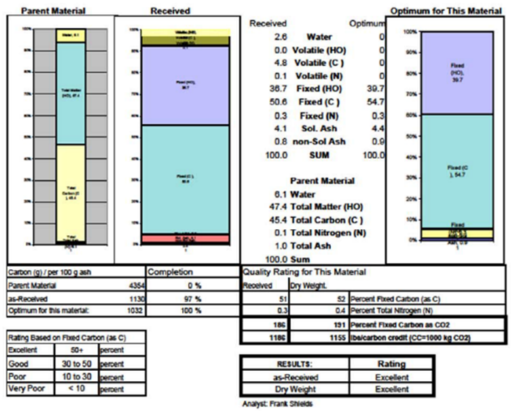


Fig. 7 - Biochar composition analysis reports produced with the DRAGON system

The analysis shows that the biochar resulting from the pellet gasification is of very good quality, to be used as a fertilizer in agricultural soils.

Fig. 8 presents an advanced gasification reactor for waste processing, made by the KBI Group company *(*** http://www.htcw.info/images/index_page/long_form.pdf. 2014)*

The high range of temperatures at which it operates (1500-2500 °C), superior to those in ordinary gasifiers, is obtained by injecting technological oxygen into the reactor.

Thanks to these temperatures, the gasifier can process with maximum yields a very wide range of urban and industrial waste of an organic and inorganic nature, such as: toxic waste, varnishes and paints, rubber (including used tires), batteries and electronic components, asbestos, metal scraps, clinical waste, paper, composite materials, residual oils, etc. Unlike conventional gasification, thanks to the reactions that occur at high operating temperatures, no ash or toxic combustion gases result.

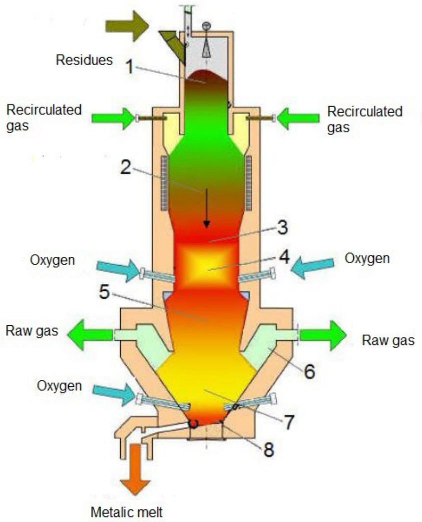


Fig. 8 - Gazeification technology HTCW
1-drying; 2-pyrolyses;3-gazeification;4-oxidation; 5-reduction;6-outlet gases;7-oxidation; 8-melting

For the detailed analysis of the processes that occur in the installations with gasification and pyrolysis processes, the block diagram presented in fig.9 will be analyzed; this is the block diagram of the general structure of the thermal energy and biochar production facilities in a combined regime: gasification + pyrolysis. Biomass and air enter in the system and thermal energy comes out that can be used for heating and biochar processes. The system includes: the gasification reactor, the gas burner and the anaerobic pyrolysis reactor.

Tab. 2 presents in detail the thermochemical processes that are performed in this type of gasifier, depending on the temperature range.

Table 2

The thermochemical processes in the HTCW reactor

Temperature	Thermo-chemical process
100-200 ^{0}C	Drying of residues, removal of water
250 ^{0}C	Deoxidation; desulfurization; elimination of constituent water and carbon dioxide; depolymerization
340 ^{0}C	Cracking of aliphatic bonds; the separation of methane and other aliphatic products begins
380 ^{0}C	Carbonization
400 ^{0}C	Breaking C-O and C-N bonds; separation of heteroatoms
400-600 ^{0}C	Conversion of bitumens into melted oils and tars
600 ^{0}C	Bitumen cracking into thermally stable substances (gaseous hydrocarbons); synthesis of aromatic hydrocarbons
800-1200 ^{0}C	Gasification: synthesis of N_2/NH_3 and $H_2S/CO,S$; halogens are in vapor state (alkaline chlorides or HCl); Synthesis of mineral melting phases
1200-2000 ^{0}C	Complete decomposition of aromatic hydrocarbons, HCN and organic compounds with chlorine; Synthesis of iron melting phases
2000-2700 ^{0}C	Molecular dissociation begins; the lower range of the plasma state

Fuel gases and biochar come out of the gasification reactor. The gasification gases are sent to the burner where they mix with the pyrolysis gases leaving the pyrolysis reactor. Combustion is maintained with strongly swirled combustion air and hot flue gases are produced, which transfer a part of their thermal energy to the pyrolysis reactor for the needs of the endothermic process, and most of it leaves the system in the form of thermal energy usable in warming up processes. Biochar production temperature is one of the main factors affecting the physicochemical properties of biochar *(Leng, L.J, Huang, HJ, 2018)*. The increasing production temperature would lead to a decrease in aliphatic and dissolvable fraction and an increase in aromatic and undissolved portion *(Wang L., Weller, C., et al, 2008)*.

In the pyrolysis reactor, under anaerobic conditions, a pyrolysis process takes place resulting in an average of 25% biochar and 75% pyrolysis gases that are burned in the burner.

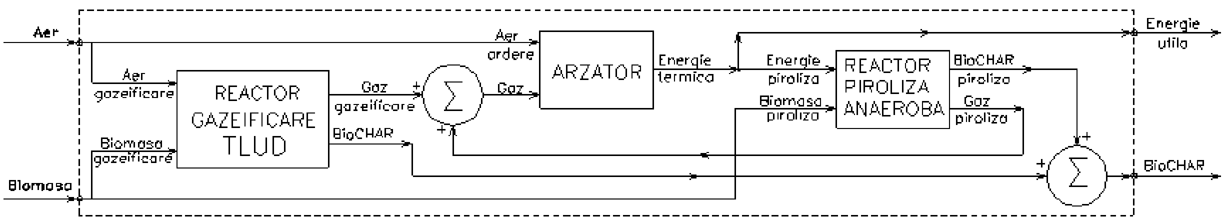
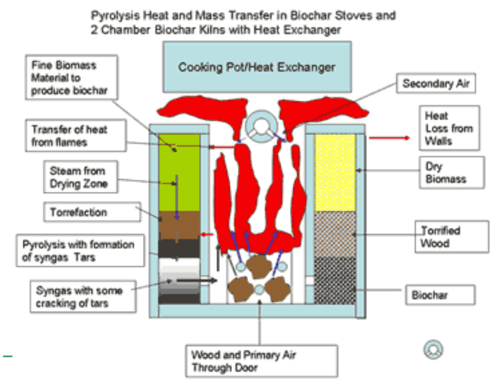


Fig. 9 - Block diagram for combined producing of energy and biochar

Achievements in the application of this structure are: the ANILA type stove, fig.10, designed by Professor RV Ravikumar, from the University of Mysore, India and Zmart Ztove type stove of 4 kW, fig.11. *(LaFontaine, https://www.drtlud.com, 2016),*of which design in section was published by Tom Miles in 1992.

The device is part of the structure with parallel reactors, which also produces thermal energy and biochar, at household level.



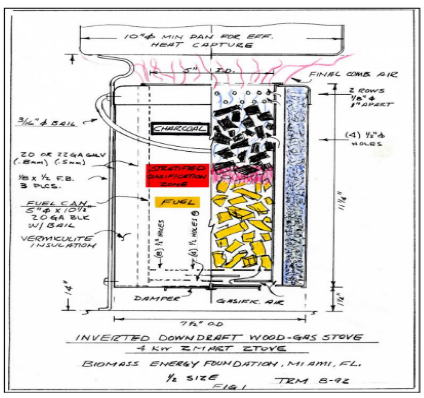


Fig. 10 - Functional scheme of ANILA type stove **Fig. 11 - Functional scheme of Zmart Ztove type stove of 4kW**

The devices has a structure with two concentric reactors, the outer one producing biochar, which does not enter into another combustion process. The inner reactor, intended for the TLUD type micro-gasification process, is filled with chopped biomass, from which, through gasification, gas is produced, which, through combustion, produces the heat necessary to maintain the pyrolysis of the biomass in the outer reactor.

The outer reactor, in which an anaerobic environment is maintained, is filled with biomass that will be carbonized. The inner reactor wall is very hot, it transmits heat to the biomass in the outer reactor, which enters the anaerobic pyrolysis process. The pyrolysis gases produced pass through holes into the inner reactor, where they are completely burned in the combustion chamber producing useful thermal energy. It is a batch-type process with reactors mounted in parallel, which reduces the height of the installation and makes it easy to handle.

In order to obtain a quality biochar, however, it is necessary to increase the pyrolysis temperature above 500^0C, by insulating the outer wall of the pyrolysis reactor.

Another variant is the structure with reactors mounted in series (*Belonio, A. T., 2005)*. A first demonstrative achievement is the system made by Jolly Roger (2012) fig. 12.

It consists of a TLUD gas generator with a 200 l volume reactor at the bottom, on which a 120 l volume pyrolysis reactor is mounted, heated by the combustion gases and which through the perforated bottom transfers the pyrolysis gases to the burner, contributing to the heat transfer to the pyrolysis reactor.

Fig. 12 - Artisanal biochar and heat production system made by Jolly Roger

Noting that the artisanal system produces quality biochar at a low production cost, the structure and process were taken over by the company BioCharWorks (NY, USA), which designed, tested, produces and markets the systems of the family - A BIO-ENERGY CONVERTER *(NREL, "PWWatt", 2014)*

- HYBRID 250, mobile system mounted on a semi-trailer, fig. 13;
- HYBRID 500, stationary installation, fig. 14.

Fig. 13 - Heat and biochar production installation type HYBRID 250

Fig. 14 - Heat and biochar production installation type HYBRID 250

Energy module with TLUD micro-gasification process

The functional diagram of a TLUD generator with a coupled burner is presented in fig. 15. The micro-gasification process is fed with air from a variable speed fan.

Figure 16 shows the functional diagram of a TLUD generator where the gas burner is separated from the gas. LPG is a combustible gas with a low calorific value and for efficient combustion specialized FLOX type burners are used. The biomass is introduced into the reactor and rests on a grate through which air for gasification passes, from bottom to top. The initialization of the process is done from the free upper part of the biomass layer.

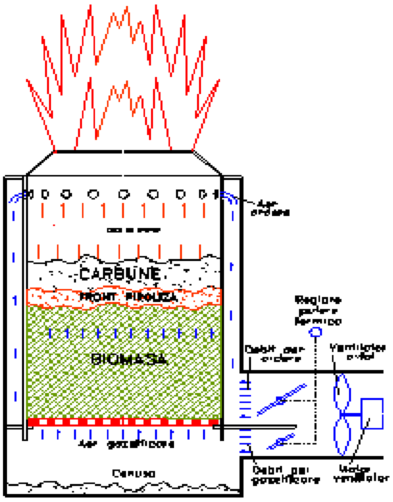


Fig. 15 - TLUD generator functional scheme with coupled burner

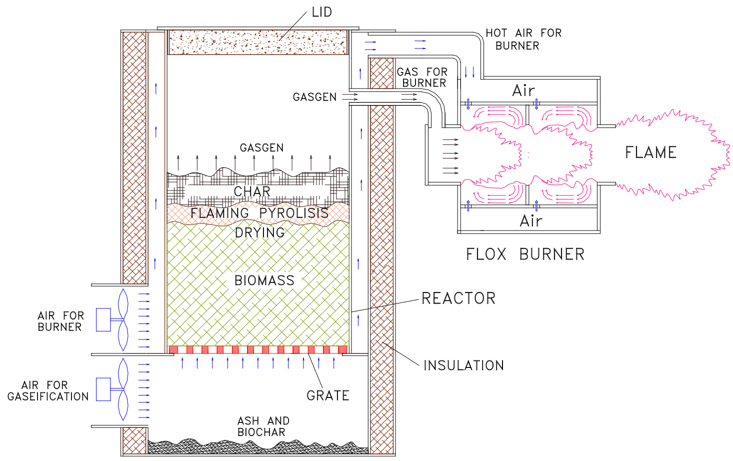


Fig. 16 - TLUD generator of a functional scheme with specialized burner type FLOX

The thermal energy is obtained by burning the hot gas generated in the pyrolytic phase; it mixes with the preheated combustion air introduced into the combustion zone through the holes arranged at the top of the reactor. The highly turbulent mixture burns with a flame at the upper nozzle of the generator with temperatures of 900-1000 ºC. To adjust the required thermal power, the air flow for gasification Dag and for combustion Dard is varied, with two flaps, mechanically coupled, or by varying the fan speed.

The TLUD process is with a fixed layer of biomass and as a result the generator operates in batch mode with recharging.

The gasification process is done with a low intensity, with specific hourly consumptions of 80 – 150 kg.bm/m^{2}h, which leads to low specific powers for the reactor, 250 – 350 kW/m^2.

The slow process maintains the superficial velocity of the produced gas at very low values $v_{sup} \leq 0.06$ m/s, which ensures the reduction of free ash entrainment and at concentrations of $PM_{2.5}$ at the exit from the burner of maximum 5 mg/MJbm, a value of at least five times lower than the current norms imposed for thermal generators with solid fuel.*(Belonio, A. T. 2005),(Mukunda, 2010), (Suárez,E., Concheiro,M. Jacobo Porteiro,J., 2013)*

Because a very good mixing of gas producing with combustion air is ensured, at an optimal excess of 1.4 -1.5, the concentration of CO in the combustion gases is below 2% or 0.8 g/MJbm, a value below the currently imposed rules. These aspects make the TLUD thermal generator the least polluting compared to other solid fuel thermal energy production systems.

This type of thermal energy generator was developed and used for food preparation stoves in isolated areas, working very well with a wide variety of local biomass. A remarkable example of the energy and ecological performance is the portable stove produced by PHILIPS, in which the fan is powered by electricity produced by a thermos-generator with semiconductors, mounted under the grill, being a typical example of a thermos-generator with energy independence. Some traditional ways of making coal, for example in earthen hills, are not safe and are less energy efficient. They produce large amounts of smoke that pose a health risk and is an environmental pollutant, and small amounts of biochar are obtained from the initial biomass. Biochar, produced during pyrolysis, is valuable in agriculture and the environment *(Matache, G, Maican E., et al., 2017).*

RESULTS

The thermal generator, currently in the design phase, will equip the convective dryer with energy independence from the electricity network, proposed to be realized within the project.

It will include the reactor for biomass gasification and combustion of the gas produced by gasifier and the air-air heat exchanger.

The TLUD (Top-LitUp-Draft) type reactor, with batch operation, is filled with biomass and the ignition to initiate the gasification process is done in the top layer.

A slow burn takes place in the reactor, and the layer of incandescent coal (also called the oxidation front) continuously descends, consuming the biomass in the reactor. Due to the heat radiated by the oxidation front, the biomass heats up, dries and then enters a rapid pyrolysis process, at which point volatiles are released from the biomass. The volatiles pass through the layer of hot coal, turning into a combustion gas called gas produced by gasifier. When the oxidation front reaches the grill, all the volatiles from the biomass have been gasified, and part of the fixed carbon has been reduced, leaving between 10 and 20% of the initial mass on the grill, in the form of sterile coal called biochar (BCH).

The burning of gas takes place in the upper part of the combustion chamber of the reactor; the combustion gases produced give up thermal energy to the air-air heat exchanger located in the drying chamber of the convective dryer.

The gasification process is characterized by very low values of the superficial velocity of the gases through the oxidation front (0.03-0.06 m/s), which leads to a very high energy conversion efficiency, in the pyrolytic phase, of approximately 93-95%).

The thermal generator can work in the CHAB concept (Combined Heat and Biochar production), that is, the simultaneous production of heat and biochar.

Research in the field demonstrated that in the nominal mode of operation of the thermal generator, the energy conversion efficiency η_{conv}=0, 95, and the combustion efficiency η_{ard}=0.98. The specific useful thermal power has values from 300 to 360 kW/m^2. *(Murad, E. 2016).* A specific characteristic of TLUD gas generators is the useful energy density of the reactor volume η_{ard}=0,98 with values of 0.93...2.56 MWh/m^3, a parameter that represents the usable energy stored in the biomass in the reactor.

Ecologically, the performance of TLUD thermal generators is given by:

- the CO emission reported at the reactor section, with an average value of 6 kg CO_2/m^{2}h, which corresponds to a concentration of 2% CO/(CO+CO_2) in the combustion gases;

- the specific PM emission which is very low, between 4.4 and 5.3 g/m^{2}h, practically a smokeless conversion of biomass into heat;

- the specific CO_2 balance corresponding to biochar incorporated as an amendment in agricultural soils, with very high values between 120 and 180 kg CO_2/m^{3}bm or 400 kg CO_2/tbm in biochar regimes and obviously zero when the biochar produced is gasified in the second phase.

By continuing the research with the combustion test equipment, presented as a physical achievement, suitable for low power TLUD type gasifiers, the study and control of combustion at TLUD type equipment can be deepened, which can transfer these devices from food preparation equipment category to automated heating equipment category similar to gasification boilers.*(Pavel, I., Chirita A.-P., 2021)*

The energy and economic difference between the two exploitation regimes is highlighted by the parameter - useful energy produced from biomass - which in the regime without biochar has the value 1 when 28% more thermal energy is obtained compared to the first phase. If we move on to the biochar gasification phase, in the end a zero CO_2 balance is obtained.

An economic estimate of the costs of thermal energy production with TLUD generators shows that the possibility of using locally available biomass, chopped and dried at the place of use under normal conditions, leads to reduced costs for the thermal energy produced if the biochar is used as an agricultural amendment or filterable material.

Compared to the gasification of pellets, the cost of primary energy produced from local biomass simultaneously with the utilization of biochar is at least 4.4 times lower.

CONCLUSIONS

1. The thermal generator intended to equip the convective dryer with energy independence will be designed for a power of 10 kWt. It will include the biomass gasification reactor and gasification gas combustion and the air-air heat exchanger, located in the drying chamber.

2. The TLUD (Top-LitUp-Draft) type reactor, with batch operation, is filled with biomass and the ignition to initiate the gasification process is done in the top layer. The biomass combustion chamber will be provided

with an outer cylindrical jacket. The air required for the gasification process will be introduced at the bottom of the combustion chamber, and the air required for the gasification gas combustion will be introduced through the circular space between the two concentric cylinders (combustion chamber and outer jacket). Moving through the warm exterior of the combustion chamber, the combustion air swirls and preheats, which leads to an increase in reactor efficiency.

3. Compared to hot water-hot air heat exchangers, where the drying agent-hot air is obtained by circulating an external air current through a hot water radiator, the flue gas-hot air heat exchanger (the drying agent), eliminates the heat transfer step of the energy from the combustion gases to the water in the radiator.

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